Delay and Phase Calibration in VGOS Post-Processing

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Abstract In recent years, large amounts of data have begun to flow through the VGOS pipeline, and significant real-world issues are now being encountered in the fringe-fitting process. In order to create a high-quality geodetic observable it is important to minimize the sensitivity of the group delay to instrumental parameters that may change over time, while at the same time maximizing the amount of information that is extracted. This paper addresses a number of topics relevant to those goals, such as matching of delays in polarization products and receiving bands, and coherent phasing of the four polarization products. We describe the software that automates the somewhat tedious determination of the calibration parameters. The ionosphere is highly correlated with the group-delay observable, so its accurate characterization and removal are central to the determination of the calibration parameters.

Keywords VLBI, calibration, ionosphere

1 Introduction

The VLBI Global Observing System has been many years in development, but only relatively recently has it started to generate appreciable quantities of data. Its wide spanned bandwidths, dual-linear polarization, and the desire to push the envelope on short, and thus weak, observations lead to added complexity during the post-processing stage. It is necessary to exercise extra diligence during the post-correlation processing, with additional calibration steps inserted, in order to ensure that a minimum of information is lost from the raw observations.

MIT Haystack Observatory

2 Characteristics of the Observations

The RF spectrum of the VGOS system spans about 10 GHz, and it is split into four bands, each of 512-MHz width. In turn, each of those bands is further broken into sixteen 32-MHz channels, with eight in each linear polarization. Thus there are a total of 4x8 = 32 channels in each of the four polarization products (XX, YY, XY, and YX) that are produced by the correlator. The VGOS system uses a series of phase-calibration tones, which are separated by 5-MHz intervals. The principal use of these tones is to remove instrumental differences in channel phase incurred in the signal path between the receiver and the samplers. A secondary purpose, though, is to adjust for inter-channel variability in delay. This is done in the fourfit program by (in essence) seeing how the phase within each channel varies as a function of tone frequency.

3 Pseudo Stokes-I Mode

In order to extract the most accurate group delay estimate from the four polarization products coming from the correlator, it is desirable to coherently combine them in a single fit, yielding a single estimate of the group delay. In principle, it would be possible to have no fringes detected in any one of the four products, but to still have detectable fringes in their coherent sum. A formulation for combining the products was given by Corey (2011), producing a quantity similar to the Stokes intensity, or I, product:

$$I = (\overline{X_a \star X_b} + \overline{Y_a \star Y_b})\, cos(\Delta p) + (\overline{X_a \star Y_b} - \overline{Y_a \star X_b})\, sin(\Delta p) \quad (1)$$

where Δp is the differential parallactic angle between sites a and b, and $\overline{X_a \star Y_b}$ is (for example) the time-averaged correlation product of site a's X polarization with site b's Y polarization. The trigonometric functions of the parallactic angle difference account for the projection of the linear polarizations into one other.

4 Optimal Determination of Polarization-dependent Phase and Delay Offsets

The combination of the four polarization products into a single Stokes-I observable without too much loss of signal-to-noise ratio (snr) due to insufficient coherence (see Figure 1) requires matching of both residual phase and delay. Two products will suffer at most a 1% decoherence if either of two conditions are true:

- the phases differ by 8°, and
- the multiband (group) delays differ by 10.2 ps. This corresponds to a slope in the phase vs. frequency relation, and causes a peak-to-peak phase change of 28° across the current VGOS RF bandwidth of 7.65 GHz.

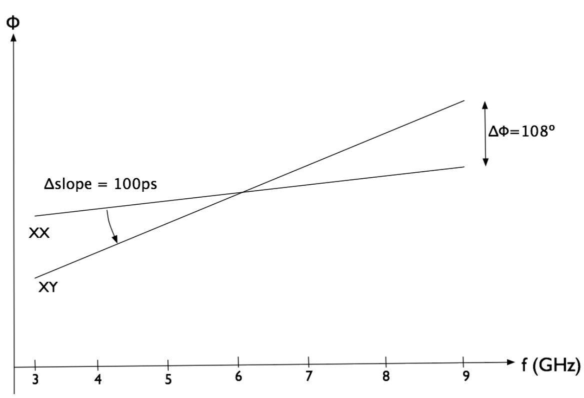

Fig. 1 Example of mismatching residual group delays between two polarization products, which leads to reduced coherence across the VGOS observing range. In this extreme example, the data near the ends of the range are actually anti-correlated with the bulk of the data, and would reduce the fringe amplitude.

These values, 8° and 10 ps, should be considered as upper bounds in the allowable discrepancy between polarization products prior to coherent combination.

4.1 *Fourphase*

In order to accommodate the phase and delay offsets, the *fourfit* program has been modified to allow both a phase and a delay offset between the two polarizations at each station. These offsets must be set for an observing session to values that ensure the coherence of all four polarization products going into the fringe fits. A new program, *fourphase*, has been written to automate the process of finding the offset phase and delay values. It does so by going through the following steps:

1. On each baseline, such as baseline ab in Figure 2, a single value of the differential TEC, or ΔTEC, of the ionosphere is found by performing fringe-fitting ionosphere searches on each polarization product, and then applying snr-based weights to find the optimal value of ΔTEC for that baseline.
2. The baseline ΔTEC values are then used in a weighted least-squares fit to find an optimal set of (relative) station-based TEC values.
3. Each baseline then has four fringe-fits (one per polarization product) performed using the TEC estimates from Step 2. This produces output data consisting of a multiband delay, a phase, and an snr for each of the four products. For n stations, this step produces $2n(n-1)$ phases and delays.
4. Using the data from Step 3, a global weighted least-squares solution for the Y offsets relative to X (e.g., $Y_a - X_a$) in both delay and phase is produced for each of the n stations.
5. For convenience, a *fourfit* control file is written out, with the delay and phase parameters that were found in the least-squares fit of Step 4.
6. Based upon the new values for the parameters, new fringe fits are performed and various statistical quantities are calculated to verify that the fitting process was successful.

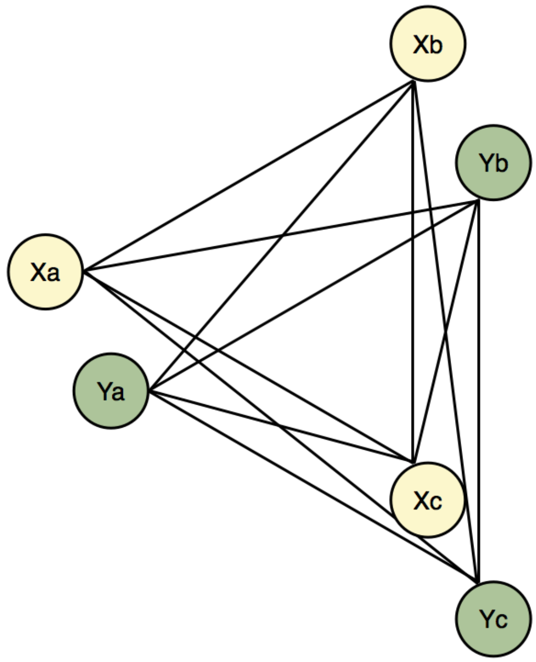

Fig. 2 An example of the geometry of the phase and delay offset fitting process in the three-station case. Stations a, b, and c, each have two polarizations (e.g., X_a and Y_a), and each baseline has four polarization products (e.g., X_aY_a, Y_aY_b, X_aY_b, Y_aX_b) that are measured.

5 The Effect of the Ionosphere

In the VGOS system, due to the multiple bands, wide RF spanned bandwidth, and the desire to allow observations with low snr, the ionosphere is estimated and removed at fringe-fit time, rather than later during database creation (for details on the algorithm employed, see Cappallo, 2014). Briefly, the fringe fit in *fourfit* is performed by finding that group delay which maximizes the coherent sum over time and frequency of the fringe phasors residual to the correlator model. When the ionosphere is fit, *fourfit* simply and robustly searches over a grid of potential differential ionosphere TEC values, in order to find the maximum coherent phasor sum. This trial value is then improved by iteration on finer grids, followed by a parabolic interpolation of the gridded values. This method of finding the maximum coherent sum with respect to the group delay has been shown to be equivalent to using least-squares estimation in the region of the maximum.

5.1 Correlation of the Ionosphere with the Multiband Delay

Despite the wide distribution of the observing bands, the differential TEC parameter is still highly correlated with the group-delay estimate. For that reason we determine the errors in the delay and TEC estimates by performing a covariance analysis using linear least squares. Let us model the observed phase as a function of frequency as follows

$$\phi(f) = \tau_g * (f - f_0) + \phi_0 - 1.3445/f * \Delta TEC \quad (2)$$

where:

ϕ phase (rot)
f frequency (GHz)
f_0 *fourfit* reference frequency (GHz)
τ_g group delay (ns)
ΔTEC differential TEC (TECU $\equiv 10^{16}/m^2$)
ϕ_0 phase at f_0 (rot)

The constant phase parameter, ϕ_0, might be usefully estimated at a variety of reference frequencies. In the future, it is possible that the broadband system will use phase delays referenced to a constant phase at DC. For now, though, *fourfit* currently performs a group-delay fit to the slope of phase vs. frequency just over the RF region of the frequency channels that were employed, and it produces a group delay along with a phase at a centered reference frequency. *fourfit's* algorithm, which maximizes the coherent sum of the counter-rotated phasors, has the effect of solving for the mean phase over the sampled frequency channels. The reported standard deviation for the phase is simply $1/snr$ radians. This standard deviation needs to be adjusted if the reference frequency is not equal to the mean frequency, as there is then a term taking into account the uncertainty in the group delay, multiplied by the difference between the reference frequency (at which the phase is reported) and the mean frequency of the sequence.

By performing a covariance analysis using the phase model in Equation 2, we find that the current VGOS observing frequency sequence leads to a correlation coefficient of 0.93 between τ_g and ΔTEC. This somewhat ill-conditioned state of affairs can be seen graphically in Figure 3, which shows an idealized noise-free case of fringe amplitude as a function of ΔTEC and τ_g. The irregular frequency spacing of

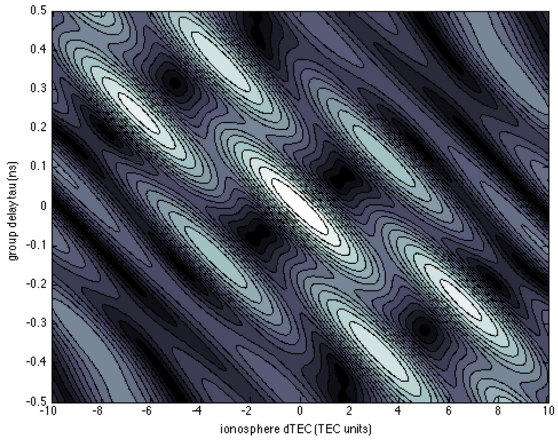

Fig. 3 Fringe amplitude as a function of differential TEC (ΔTEC) and group delay (tau). Synthetic data based upon the current VGOS frequency sequence with a flat spectrum and no added noise were used.

channels results in islands of coherence, of which the central peak is the highest. The diagonal elongation demonstrates how a modest amount of added noise might cause a large shift in tau and an offsetting shift in ΔTEC along the preferred symmetry axis.

$$\sigma_{mbd} = 1/(2\pi \cdot f_{rms} \cdot snr) \tag{3}$$

The previous *fourfit* group delay error calculation (see Equation 3), did not take the ionosphere into account, and was based solely upon rms spanned bandwidth and snr. As such, it was an underestimate of the true error, as it did not take into consideration the extra degree of freedom introduced by the ionospheric TEC. We find that the estimate of the VGOS group-delay standard deviation increases by about a factor of about 2.6 when the ionosphere is simultaneously estimated.

6 Conclusions

The process of determining appropriate phase and delay offsets for each VGOS station certainly makes the job of post-processing more complex, but it is unavoidable. Software has been written to ease the burden. On the other hand, solving for the ionosphere does not add to the serial complexity of the post-processing operations, but it is fairly demanding in terms of computing resources. When the ionosphere is solved for, it is essential that the group delay error properly reflects the added uncertainty due to the ionosphere fit.

Acknowledgements

Arthur Niell, Bill Petrachenko, and Brian Corey took part in discussions that produced significant ideas related to this work.

References

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